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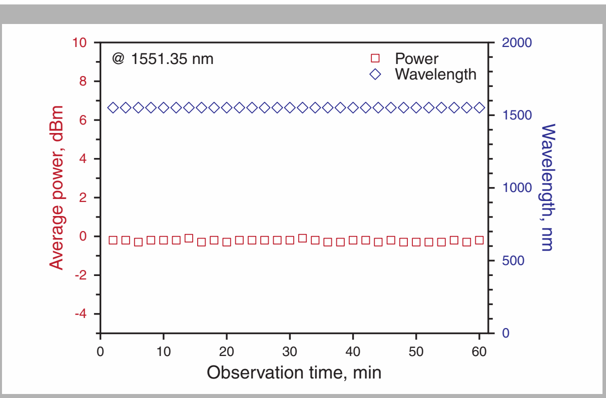
Abstract: In this investigation, we propose and demonstrate a stable and wavelength-tunable erbium-doped fiber (EDF) ring laser scheme with external-injected Fabry-Perot laser diode (FP-LD) technology, in single-longitudinal-mode (SLM) output behavior. Here, the output power and side-mode suppression ratio (SMSR) of the proposed laser scheme can be obtained between –3.9 and 1.3 dBm and 30.1 and 50.5 dB in the operating wavelengths of 1523.65 and 1561.50 nm with 1.12 nm tuning step, respectively, according to the output mode-spacing of FP-LD used. Besides, the lasing stabilities of output power and wavelength are also investigated and discussed.



Short-term observation of the proposed fiber laser is measured at the lasing wavelength of 1551.35 nm initially

Utilizing erbium fiber ring scheme and Fabry-Perot laser diode for stable and wavelength-tunable laser in single-longitudinal-mode output

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1. Introduction

Stable and wavelength-tunable single-frequency was needed in the fiber ring lasers could be employed in wavelength-division-multiplexing (WDM) communications and fiber-optic sensor systems [1–8]. Conventionally, the tunable bandpass filter (TBF), Fabry-Perot tunable filters (FP-TF), and fiber Bragg grating (FBG) could be used inside fiber ring cavity to provide wavelength-selecting [9–11]. However, it was insufficient to stabilize the lasing wavelength and power of a fiber ring laser due to the mode-hopping effect. To overcome the unstable optical output, several methods were used to obtain a single-longitudinal-mode (SLM) operating, such as integrating two cascaded FP-TF of widely different free spectral ranges (FSRs) into cavity [12,13], using a compound ring resonator composed of a dual-coupler fiber ring and dual-ring scheme [14,15], adding an extra ITU-grid periodic filter in the optical loop [16], and utilizing a unpumped erbium-doped fiber (EDF) inside fiber loop to serve as a saturable-absorber-based filter [11,17], have been proposed and investigated.

In addition, to achieve and lase the SLM wavelength, using multi-ring and sub-ring schemes for fiber laser were also discussed and reported [18–22]. However, the multi-ring scheme would result in the longer cavity length and it was hard to obtain the SLM output. In this investigation, using an EDF ring laser scheme with external-

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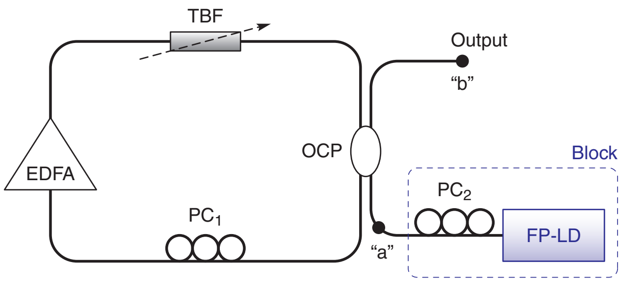

Figure 1 (online color at www.lphys.org) Experimental setup of the proposed stabilized and wavelength-tuning EDF ring laser scheme. PC – polarization controller, OCP – 1×2 optical coupler, TBF – tunable bandpass filter, and EDFA – erbium-doped fiber amplifier

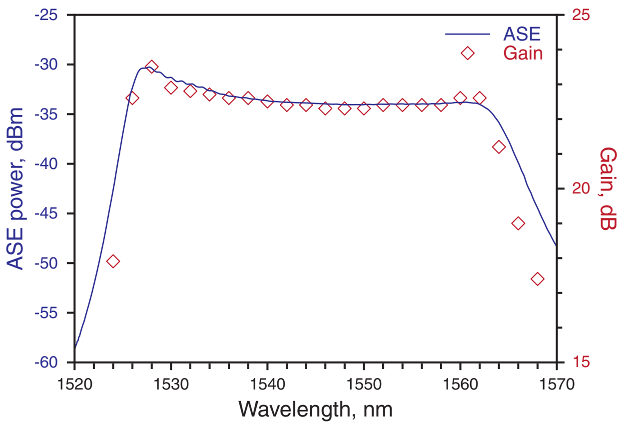

Figure 2 (online color at www.lphys.org) Output ASE spectrum and gain profile of the EDFA used without the ring structure while the 980 nm pumping laser operates at 215 mW

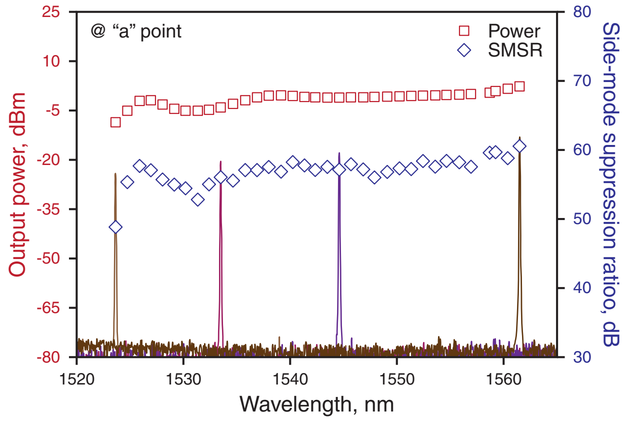

Figure 3 (online color at www.lphys.org) Output spectra, output power, and SMSR of traditional fiber ring laser (without "Block"), observing at "a" point in Fig. 1, in the wavelengths of 1523.65 and 1561.50 nm

injected Fabry-Perot laser diode (FP-LD) technique for the stabilized and wavelength-tunable output has been proposed and experimentally investigated. Moreover, the output characteristics of the proposed fiber laser have also been discussed, such as the wavelength-tuning range, output wavelength and power stabilities, and side-mode suppression ratio (SMSR) etc.

2. Experiment and results

Fig. 1 presents the experimental setup of the proposed stabilized and wavelength-tuning EDF ring laser scheme. The proposed fiber laser is consisted of a commercial erbium-doped fiber amplifier (EDFA), a TBF, a 2×2 and 50:50 optical coupler (OCP), two polarization controllers (PC_1), and a "Block". The "Block" is constructed by a PC_2 and a multi-longitudinal-mode (MLM) FP-LD. The two PCs in the experiment are used to control and adjust the polarization status and maintain the maximum output power. The TBF with a 3-dB bandwidth of 0.4 nm, which can be operated in the wavelengths of 1525 and 1560 nm, is employed to filter amplified spontaneous emission (ASE) spectrum and select lasing wavelength inside the ring cavity. In this measurement, the lasing wavelength and output power can be measured by using an optical spectrum analyzer (OSA) with a 0.01 nm resolution and a power meter (PM).

Fig. 2 shows the output ASE spectrum and gain profile of the EDFA used without the ring structure while the 980 nm pumping laser operates at 215 mW. The total output power of ASE is measured at –3.6 dBm. The gain spectrum in the wavelength range of 1526 to 1564 nm and the maximum gain is 23.5 dB at 1528 nm for the –20 dBm input signal power were measured as seen in Fig. 2.

When the proposed EDF ring laser removes the "Block", the proposed ring laser will become to traditional ring laser scheme as shown in Fig. 1. Hence, Fig. 3 shows the output spectra of traditional fiber ring laser (without "Block"), observing at "a" point in Fig. 1, in the wavelengths of 1523.65 and 1561.50 nm. Besides, Fig. 3 shows the output powers and SMSRs *versus* the different wavelengths in the operating range. The obtained output powers and SMSRs were between –8.6 and 2.3 dBm and 48.8 and 60.5 dB, respectively. In addition, the spectra of output power and SMSR also match the gain spectrum of EDFA used, as shown in Fig. 2 and Fig. 3. However, the measured lasing wavelength of Fig. 3 is unstable in the effectively operating range due to the mode hopping characteristic [9].

Recently, using optical injection technology in fiber laser scheme to retrieve SLM output was investigated and discussed [23–25]. Hence, in the experiment, to achieve stable and wavelength-tunable fiber laser in SLM, we add the "Block" to connect the traditional fiber laser in Fig. 1. In the experiment, the TBF inside EDF ring cavity was used to select a lasing wavelength to align one output mode of FP-LD for external injection. Here, the thresh-

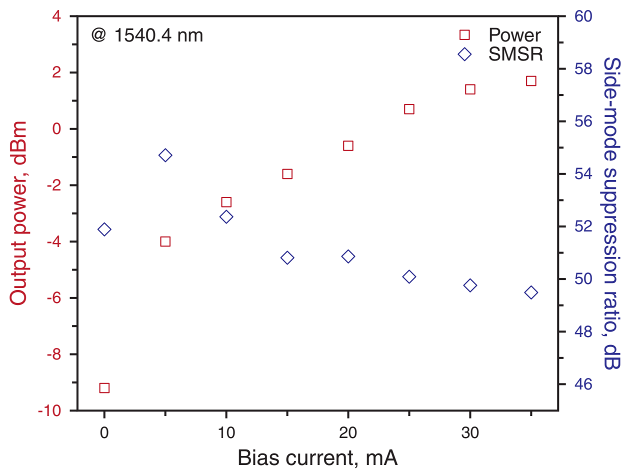

Figure 4 (online color at www.lphys.org) Output power and SMSR from the external-injected FP-LD *versus* different operating currents from 0 to 35 mA under the same injected power of –0.6 dBm at the lasing wavelength of 1540.40 nm at the temperature of 25°C

old current and mode spacing of FP-LD used are 10 mA and 1.12 nm. To realize the output performance of the "Block" first, different operating current of FP-LD under the same external-injected power is used in the measurement. Therefore, Fig. 4 shows the output power and SMSR from the external-injected FP-LD versus different operating currents from 0 to 35 mA under the same injected power of –0.6 dBm at the lasing wavelength of 1540.40 nm at the temperature of 25°C. When 0 mA is applied on FP-LD, the proposed fiber laser can obtain a –9.2 dBm output power, as seen in Fig. 4. With the increase of operating current of FP-LD gradually, the output power of the laser is also increase, as also illustrated in Fig. 4. However, the maximum SMSR of 54.7 dB (with –4 dBm output power) can be achieved while the FP-LD is at 5 mA. Furthermore, the observed SMSR will be diminished with the increase of operating current gradually. To retrieve the optimal output power and SMSR of the proposed fiber laser, the bias current of FP-LD could operate at nearly 20 mA according to the experimental results of Fig. 4.

For the proposed fiber laser in Fig. 1, the FP-LD of the proposed laser scheme would operate at 20 mA and 25°C, and its output MLM spectrum is measured in Fig. 5a. And the central wavelength of FP-LD can be obtained at 1539.15 nm with peak power of –19.6 dBm. Hence, Fig. 5b shows the output spectra of the proposed fiber laser scheme, observing at the "b" point, in the operating range of 1523.65 and 1561.50 nm with 1.12 nm tuning step according to the experimental setup of Fig. 1. Besides, Fig. 5b also presents the output power and SMSR spectra under different wavelengths. The observed output powers and SMSRs are distributed among –3.9 to 1.3 dBm and 30.1 to 53.5 dB, respectively. The maximum SMSR of

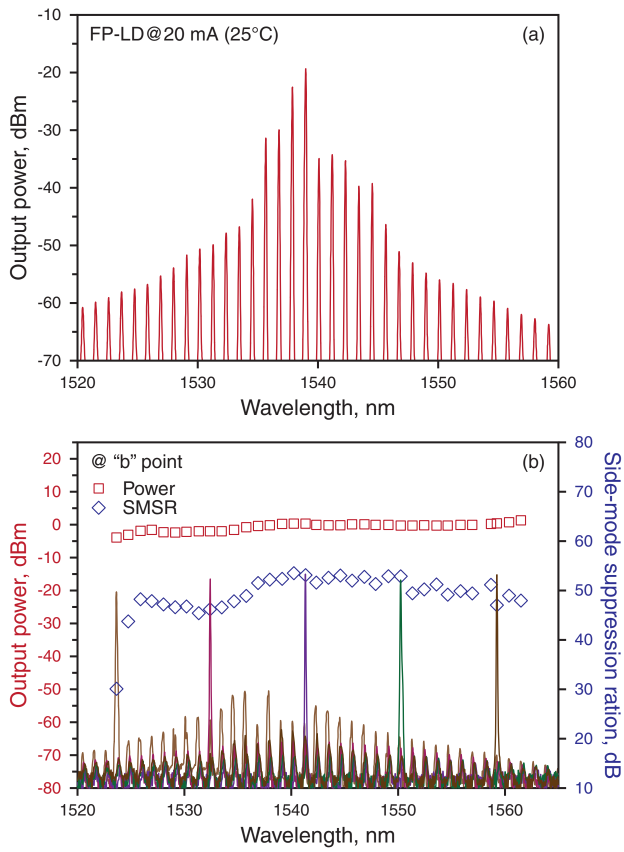

Figure 5 (online color at www.lphys.org) (a) – original output spectrum of MLM FP-LD under 20 mA bias current and 25°C temperature and (b) – output spectra, output power and SMSR of proposed fiber ring laser, observing at "b" point in Fig. 1, in the effectively wavelengths of 1523.65 and 1561.50 nm with 1.12 nm tuning step

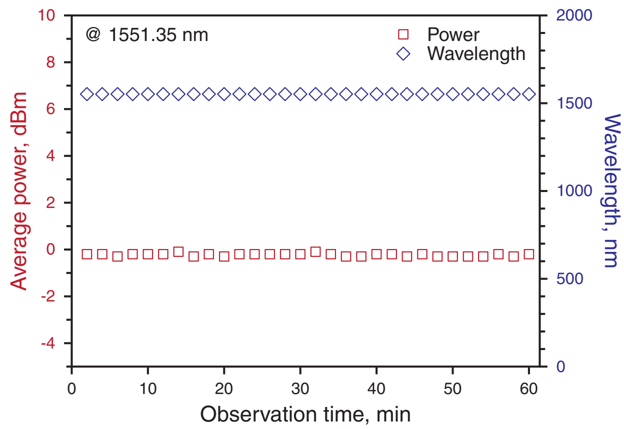

Figure 6 (online color at www.lphys.org) Short-term observation of the proposed fiber laser is measured at the lasing wavelength of 1551.35 nm initially

53.5 dB is observed at 1540.25 nm with a 0.3 dBm output power. As seen in Fig. 5b, the output power and SMSR can be larger than –2.4 dBm and 45.4 dB in the wavelength range of 1525.90 to 1561.50 nm. According to the experimental results, we can obtain the flatter output power spectrum, based on using the gain flattened EDFA module. Comparing with the past studies [21], the output power of these fiber lasers would drop gradually on the both side of output spectrum due to the smaller gain. However, if we use the gain-flattened EDFA, which was reported by our research group [22], we believe that it also can complete the same output performance.

In order to realize the output performances of power and lasing wavelength stabilities, a short-term observation of the proposed fiber laser is measured as shown in Fig. 6. The lasing wavelength is at 1551.35 nm initially and the observation time is over 60 minutes. In Fig. 6, the proposed fiber ring laser can dramatically reduce the wavelength variation ($\Delta\lambda$) to zero and power fluctuation (ΔP) of < 0.2 dB. During the four hours observation, the stabilized output of the proposed ring laser is still maintained in SLM output. The external-injection into FP-LD can lock the output mode for stabilized single frequency output. Compared with a conventional fiber ring laser scheme [9,13,15], this proposed laser has more stable output performance.

3. Conclusion

In summary, we have investigated and demonstrated a stable and wavelength-tunable EDF ring laser scheme with mode-locked characteristic of FP-LD for SLM operation in the effectively operating wavelength range. Therefore, the output power and SMSR of the proposed laser scheme can be measured between –3.9 and 1.3 dBm and 30.1 and 50.5 dB in the operating wavelengths of 1523.65 and 1561.50 nm with 1.12 nm tuning step, respectively, according to the output mode of FP-LD used. Besides, the lasing stabilities of output power and wavelength have been measured within 0.2 dB and 0 nm in the observing time of 60 minutes in the experiment.

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